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IMAGE PROCESSING APPLIED TO GRAVITY AND TOPOGRAPHY DATA COVERING THE CONTINENTAL UNITED STATES

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INTRODUCTION

A great deal of digital topographic information and gravity data exist that cover the continental United States. For instance, data sets that can be purchased from the National Oceanic and Atmospheric Adminstration (NOAA) include: (a) elevations averaged over 30 seconds of latitude and longitude for the coterminus United States and (b) approximately a half million gravity readings, where the stations are distributed across the entire country, although in an irregular manner. Both the topography and the gravity data sets are fundamental for understanding the structure of the crust and lithosphere, and especially the relationships between topography and structure (McGinnis et al., 1979; McNutt, 1981; and others).

The intent of this work is to show the applicability of fairly standard image processing techniques to processing and analyzing large geologic data sets. In particular, we have utilized image filtering techniques to interpolate between gravity station locations to produce a regularly spaced data array that preserves detail in areas with good coverage, and that produces a continuous tone image rather than a contour map. We have used standard image processing techniques to digitally register and overlay topographic and gravity data, and we have displayed the data in ways that emphasize subtle but pervasive structural features. In this paper we discuss the techniques used, briefly describe the products, and illustrate the potential of the methods by discussing subtle linear structures that appear in the processed data between the midcontinent gravity high and the Appalachians.

DATA PROCESSING TECHNIQUES

Data processing was conducted on a PDP-11/34 minicomputer with interactive image storage and display peripherals. Software is based on mini-VICAR, with a variety of applications program to conduct filtering, enhancement, and geometric operations. The reader is referred to such standard references as Moik (1980) for further information regarding general techniques used in image processing. Our software was developed partly at the Jet Propulsion Laboratory, partly at the U.S. Geological Survey, Flagstaff, Arizona, and partly by us.

For the purposes of this paper, the dynamic range of both the topography and the gravity data were first scaled to fit within the range occupied by a byte variable (i.e., 8 bits or 256 discrete values). The byte-encoded data were then stored in data arrays, where the array element spacing was 30 seconds in both latitude and longitude. For the topography, this procedure produced a regular array of byte-encoded data that had 2880 rows (latitude) and 7080 columns (longitude). The data arrays covered a latitude range from 25° to 49° north and a longitude range from 66° to 125° west.

The resulting topography data array could be displayed as an image if the byte-encoded data were converted to color or brightness values. An alternative and quite useful method of depicting topography is to generate a digital shaded relief map. Figure 1 shows such a product that was generated on a version of the data file that was first transformed to a Mercator projection, digitally reduced in size by a factor of seven, and then used to generate a

relief map. The shading process is based on assuming a photometric function for the surface (Lommel Seeliger function in our case), and then solving for the brightness to assign to a given array element location based on the local slope magnitude and direction, relative to an assumed solar azimuth and elevation (Batson et al., 1975).

The gravity data were reduced to Free air and to Bouguer anomalies courtesy of the Geopositional Department, Defense Mapping Agency Center, St. Louis, Missouri. The reference field at sea level used in the reduction was based on the 1967 International Gravity Formula, with all the data referenced to the 1971 International Gravity Standardization Net. Free air anomalies were computed from the following formulation: $\Delta g_{FA} = g + 0.3086h - \gamma$
Where: Δg_{FA} = Free air anomaly (mgals), g = reading, h = elevation, positive down to geoid, γ = theoretical gravity value.
A second order term was added to the elevation correction when the magnitude of the correction exceeded 0.1 mgals. Bouguer anomalies were computed based on a slab with density 2.67 gm/cm3 using:
$\Delta g_{BA} = \Delta g_{FA} - 0.1119h$
where Δg_{BA} = Bouguer anomaly in mgals.
Local terrain corrections were not included in the Bouguer anomaly computations.

Generating images from the gravity data presents a more complicated problem than the topographic data, since the gravity stations are not located along a regular grid. For both the Free air and Bouguer anomalies, the data were first scaled to fit within a byte variable (i.e., 256 discrete values). The scaled data were placed into an array with the same element spacing (30 seconds) and geographic coverage as the topography data array. The element

location closest to a given gravity station location was assigned the station value, thereby producing an array occupied in part by real data and in part by blank zones.

We chose to use a conceptually simple, but powerful filtering approach for interpolating between the real gravity data points. The technique was developed for processing Lunar Consortium data and was also used to produce altimetry maps from the aproximately 100,000 elevation estimates obtained by the Pioneer Venus radar mapper (Eliason and Soderblom, 1977; Pettengill et al., 1980). The technique involves use of a spatial filter that generates a moving average through the data array. The filter at any given position within the data array occupies a box of N x N elements. The mean value of the gravity anomalies for stations located within the box is used as the interpolated value for the box center, only if an anomaly value does not already exist at that location. Shifting the filter over the array and repeating the operation for each element location results in a partially interpolated data set. Blank areas still remain in zones without any data and in zones that had so little data that a user-defined statistical threshold was not met. The threshold is defined in terms of the fraction of elements within the box that must have valid data in order to replace the midpoint element with the average, assuming that the midpoint did not already have valid data.

In practice, the gravity data were processed using several filter widths, beginning with a 3 x 3 element filter and ending with a 21 x 21 element filter. The threshold was set such that at least 20% of the element locations at any given filter position must have

had real data values to be interpolated. The choice of filter sizes was governed by the station spacings, which averaged several kilometers, but varied from 100's of meters to several 10's of kilometers. A 3 x 3 element filter, for instance, covers 90 seconds of arc in both latitude and longitude, or about 3 km along a line of latitude. Note that regions with relatively small distances between gravity values were interpolated only over relatively short distances, since once an element was assigned a data value, it was not affected by later filter passes. The net effect of the filtering operations was to generate a regular array of gravity data, with original data left intact, and with interpolated data between the original values. Some areas in the array, even with a 21 x 21 element filter, still had too little data to allow interpolation. Those areas appear black in all of our displays.

The filtered gravity anomalies could be displayed as gray tone or as color-coded images. As with topography, we find that a very effective visual display is a shaded relief map. Figures 2 and 3 depict shaded relief maps for the Free air and Bouguer anomalies, respectively. Comparison of these products with previously published contour maps (e.g., Woolard and Joesting, 1964; McGinnis et al., 1979) show similar broad-scale patterns. However, the maps shown in Figures 2 and 3 have inherently more information. The reasons are threefold. First, a finer grid spacing was used to interpolate between station readings as compared to any published map that we have been able to examine. Secondly, there are as many contour intervals as there are values in a byte variable (i.e. 256). Most contour maps typically have a dozen or so contour intervals.

Thirdly, areas with a large number of closely spaced stations retain details of the anomaly patterns.

The filtered gravity anomalies can also be digitally overlayed onto the topography for a visual display of the correlations between the two variables. The technique that we used was to first convert the byte value for each element in the gravity arrays to a given color (Figure 4). The colors were chosen in such a manner that blue corresponded to the most negative anomalies and red to the most positive anomalies. Oranges, yellows, and greens were chosen to represent intermediate values. Color coded images depicting the anomaly patterns were digitally overlayed onto a shaded relief map of the topography simply by replacing the brightness component for each color with the brightness from the corresponding location in an array containing the shaded relief map. The net result is a color map, where the brightness is modulated by the shaded relief map while the color hue (dominant wavelength) and saturation (degree of purity) are controlled by the gravity anomaly values. Note that any color can be uniquely defined by a hue (dominant wavelength), saturation (purity), and brightness (Slater, 1975). Such products are shown for both the filtered Free air and Bouguer anomalies on the cover of this issue of EOS. In both cases the maps were transformed to a Mercator projection, digitally reduced by a factor of seven, and then processed as discussed above.

DISCUSSION

A sketch map showing some of the major structures evident in

the color and shaded relief maps is shown in Figure 5. For this paper we will restrict our discussion of the processed data to a portion of the midcontinent, where we have a continuing interest in the crustal structure and the relationships between basement fractures and ore deposits. Such a discussion also serves to illustrate the kinds of information that can be gleaned from topography and gravity data that have been processed in image format.

The dashed lines in Figure 5 define two major structures in the midcontinent, a feature that we call the Missouri gravity low, and the Mississippi Valley graben as defined by Kane et al. (1981) on the basis of gravity and aeromagnetic anomalies. The Missouri gravity low can be seen on the color and shaded relief maps as a 140 km wide feature that begins at a break near the southern edge of the midcontinent gravity high, extends across Missouri, and into the Mississippi embayment. In the embayment the low takes the form of a horst block called the Pascola Arch (Ervin and McGinnis, 1975). The low has an Bouguer amplitude of about 30 mgals for the region just to the northwest of the embayment. The magnitude of the anomaly is suggestive of a deep basement structure. In fact, the anomaly is consistent with an increased crustal thickness of 3 km at the Moho or with a crust that has a density of 0.1 gm/cm3 less than the surrounding areas for the first 4 to 8 km below the surface (Strebeck, 1982). Analyses of remote sensing data and ground studies for areas overlying the gravity low demonstrate that the regional fracture trends are coincident with the strike of this deep basement feature, suggesting a fair degree of control over the

pattern of faulting in the area (Guinness et al., 1982).

The intersection of the Missouri gravity low and the Mississippi valley graben has clearly served to control the emplacement of the two mafic plutons defined by Hildenbrand et al. (1977): the Bloomington intrusion to the north and the Covington intrusion to the south. The two plutons can be seen as positive anomalies in the color Free air map and as bumps on the shaded relief maps. Additionally, Figure 6 is a gray tone image of the filtered Free air data that has been contrast enhanced to show the variations in the midcontinent. In such a display, the most negative anomalies are dark and less negative anomalies are bright. The Missouri gravity low is clearly discernable and there is a suggestion of a NE-SW trending structure that, in fact, outlines the Mississippi Valley graben. The white dots represent about one thousand Earthquake epicenters recorded by the St. Louis University seismic network between 1974 and 1979 (Stauder et al., 1977). Clearly, the epicenters, which delineate the New Madrid seismic high, are concentrated in the crustal block defined by the intersection of the Missouri gravity low and the Mississippi Valley graben. Thus, the intersection of these two crustal structures seems to have provided both a zone of weakness for the emplacement of plutons, and a focus for release of strain energy via Earthquakes.

Examination of the Free air color map suggests an extension of the Missouri gravity low from the midcontinent gravity high to the northwest, perhaps as far as to the Big Horn uplift in Wyoming. The suggestion is based on an alignment of a sharp break in the Free air

anomalies with the North Platte River valley in Nebraska, and with fractures in Wyoming. The reality of such an extension must remain open to question until further study. If the extension is genetically related to the Missouri gravity low, the combined lengths of the two features would be over 1500 km. There are other structures of comparable length on the Earth, namely transcurrent faults such as the Altyn Tagh of China (Molnar and Tapponier, 1975). It is conceivable that the Missouri gravity low and the extension into Wyoming are part of a transcurrent fault system, sections of which have been reactivated during various time periods. Such an origin is also consistent with the observation that the structure cuts across the basement age and province boundaries defined by Bickford et al. (1981) in Missouri. The feature could have formed, for instance, during the postulated collision event that produced the Grenville orogeny (Dewey and Burke, 1973).

IMPLICATIONS FOR THE EARTH SCIENCES

The future will see an increased availability of a number of other large, geographically-oriented data sets that are applicable to Earth Science problems. For instance, as part of the National Uranium Resource Evaluation Program (NURE), the Department of Energy has acquired airborne digital gamma ray (net radioactivity) data, aeromagnetic anomalies, and hydrogeochemical data for most of the continental United States. Such large data sets are aptly suited for use with the kinds of techniques described in this paper. Of course, analysis of any data set requires above all the proper

framing of scientific questions. Also, the right kinds of data must be accessible to answer the questions. However, we do feel that interactive digital image processing of a variety of geographically-oriented data sets can lead to substantial advances in our understanding of the Earth.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Figure 1 - Shaded relief map depicting NOAA 30 second elevation averages for the continental United States. Numbers running vertically along the sides of the image are degrees of north latitude, while numbers along the bottom are degrees of west longitude. This and other maps in the paper are Mercator projections. The simulated sun west was set at 20° above the western horizon. Dark blocky areas are missing data.

Figure 2 - Shaded relief map depicting filtered Free air anomalies. Black areas indicate regions containing either bad data or too little data to have a statistically valid interpolations. The simulated sun was set at 15° above the western horizon. Variations in the anomalies are, in effect, illuminated as if they were a set of topographic ridges and valleys. For example, the midcotinent gravity high (43°N., 94°W.), which is a positive anomaly, stands as a ridge, while the great valley of California (37°N., 120°W.), which is a negative anomaly, appears as a trough.

Figure 3 - Shaded relief map depicting filtered Bouguer anomalies. The map was produced in the same manner as the Free air anomaly map in Figure 2. No local terrain corrections were included in computing Bouguer anomalies.

Figure 4 - This diagram shows the approximate color-coding scheme that was used to produce the color contours for the gravity anomaly maps shown on the cover of this issue of EOS. Histograms showing the fractional area occupied by each anomaly value were used to assign colors in such a manner that each color value occupies an area comparable to any other color value. About 45 discrete color values (i.e., discrete hue and saturation values) were used in each anomaly map. On the other hand, the shaded relief map versions of the anomalies each contain 256 shades of gray.

Figure 5 - Sketch map showing some of the major structures that can be seen in the gravity anomaly maps presented in this paper. The Missouri gravity low can be seen best on the shaded relief map versions of the anomalies. The two plutons are the Bloomfield pluton to the north and the Covington pluton to the south. They can be seen as red dots on the Free air color maps and as bumps in the shaded relief anomaly maps. The Bloomfield intrusion is located at about 37°N., 90°W. The Mississippi valley graben location is from Kane et al. (1981), although the outline can be seen in the shaded relief anomaly maps.

Figure 6 - Gray tone version of the filtered Free air anomalies. The map boundaries extend from 34° to 43°N., 87° to 99°W. The two horizontal lines correspond to 37° and 40°N. latitude, while the two vertical lines are 91° and

95°W. longitude. In this map bright areas have large Free air anomalies while dark areas have small (i.e., highly negative) values. The white dots are Earthquake epicenters for the period from 1974-1979 as recorded by the St. Louis University seismic network. The Bloomfield and Covington plutons are the bright circular features just to the north and south, respectively, of the epicenter cluster. The Missouri gravity low extends from a break in the midcontinent gravity high, through Missouri, and across the Mississippi valley graben. The intersections of the gravity low and the graben are the locations of the intrusions. In addition, most of the seismicity is concentrated within the crustal block defined by the intersection of the two gravity low and the graben.

CAPTION FOR COVER:

About half a million Free air and Bouguer anomalies for land stations covering the United States were spatially filtered to form a regular array of interpolated data. The anomaly values were then color-coded and overlayed onto a shaded relief map of topography. The simulated sun for the shaded relief map is from the west at 20° above the horizon. The color-coding scheme for the Free air data is approximately as follows: blue, less than -34 mgals; blue-green, -34 to -10 mgals; green -10 to -3 mgals; yellow, -3 to +10 mgals; orange, +10 to +26 mgals; red, greater than +26 mgals. The

color-coding scheme for the Bouguer data is approximately as follows: blue, less than -212 mgals; blue-green, -212 to -128 mgals; green -128 to -84 mgals; yellow, -84 to -47 mgals; orange, -47 to -17; red, greater than -17 mgals. See the article in this issue of EOS for further information.

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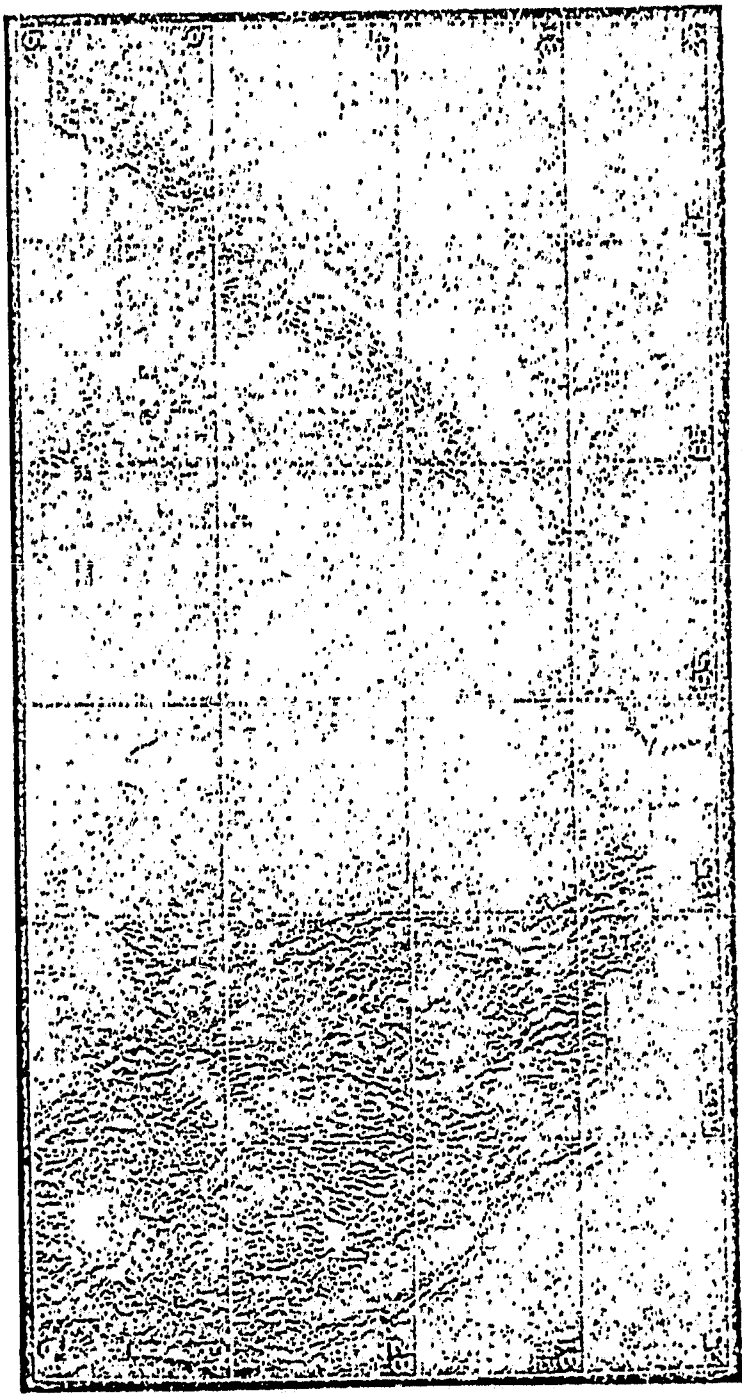

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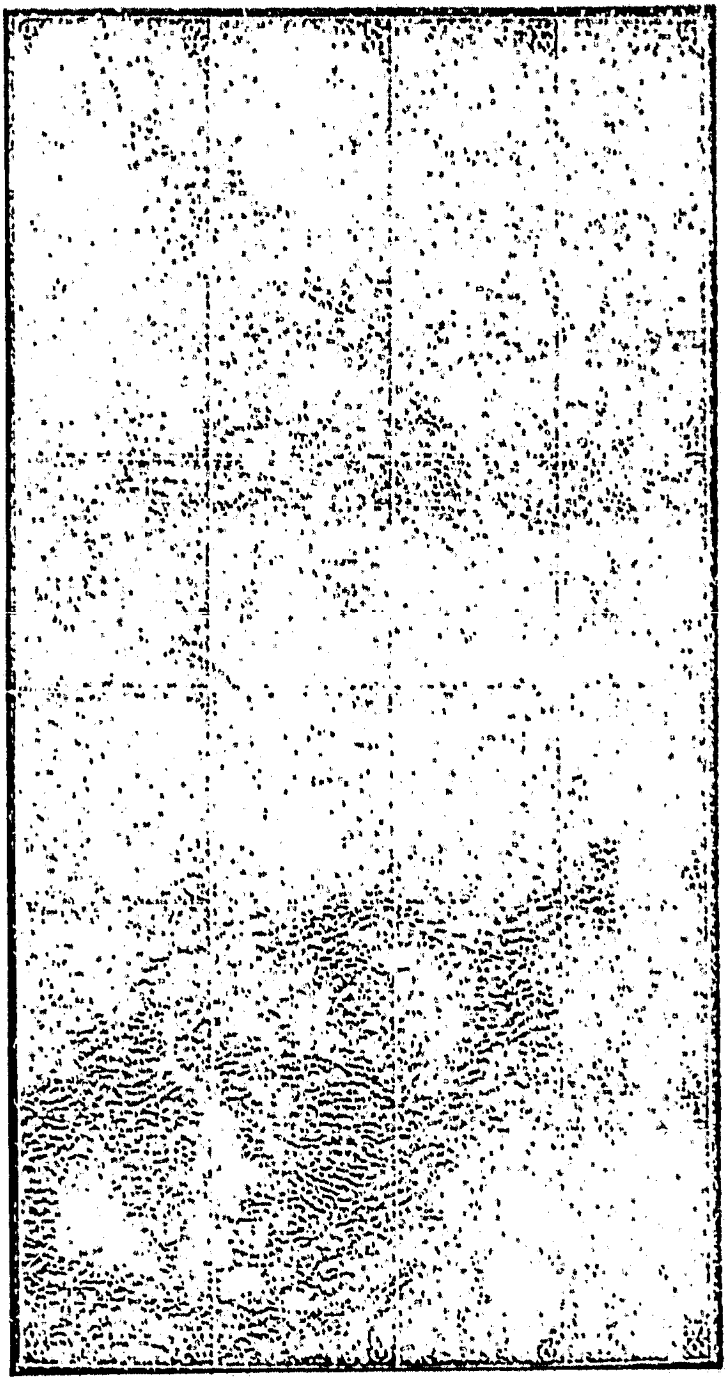

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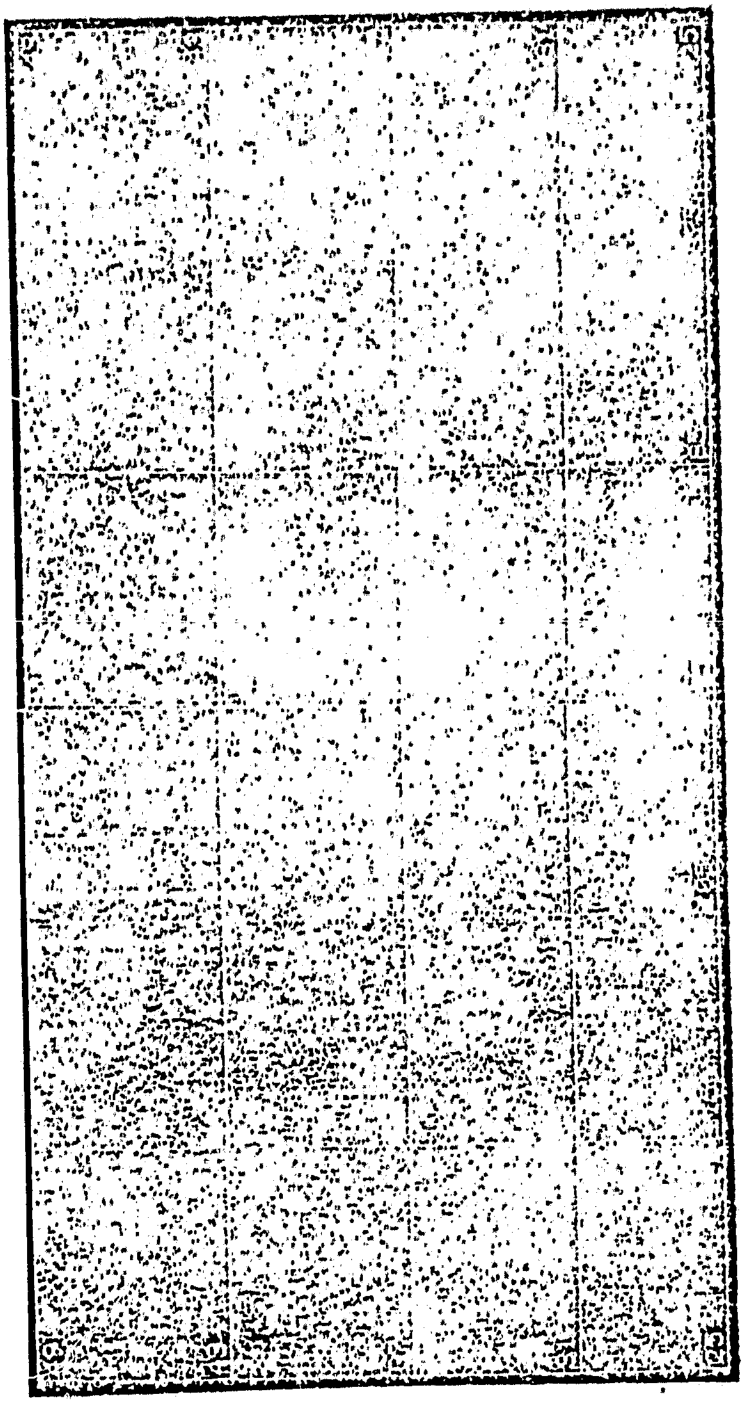

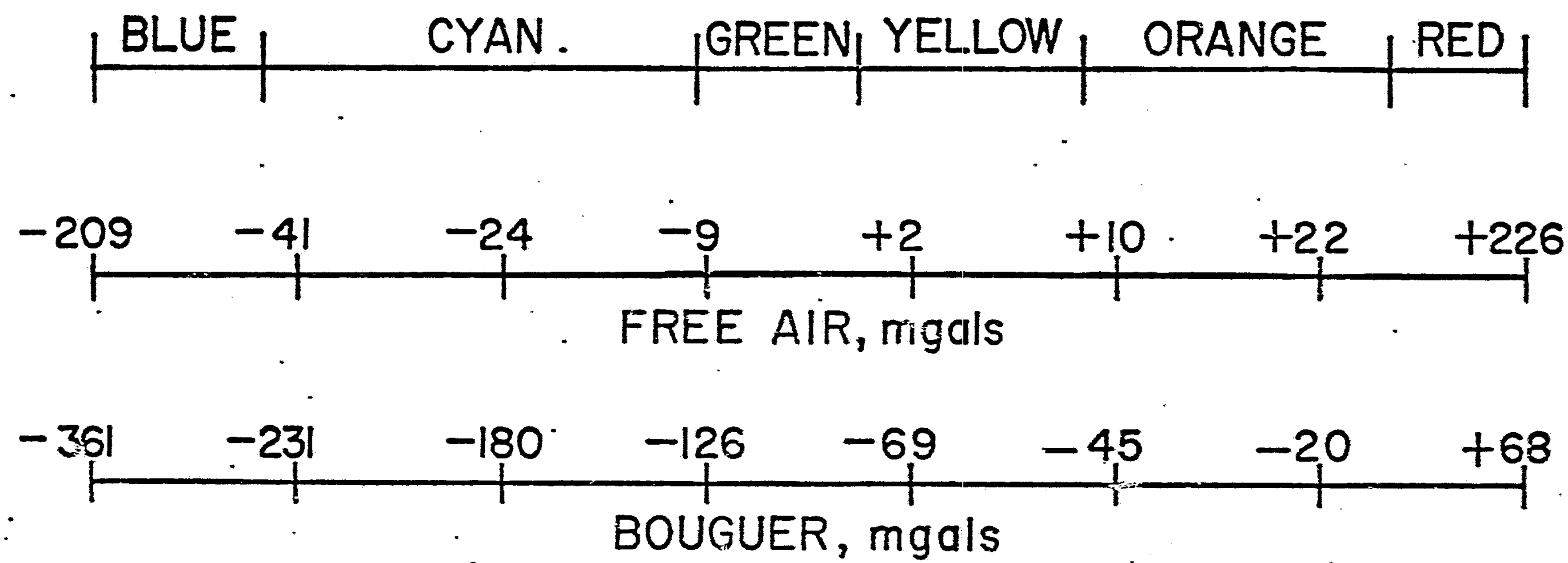
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Figure 4

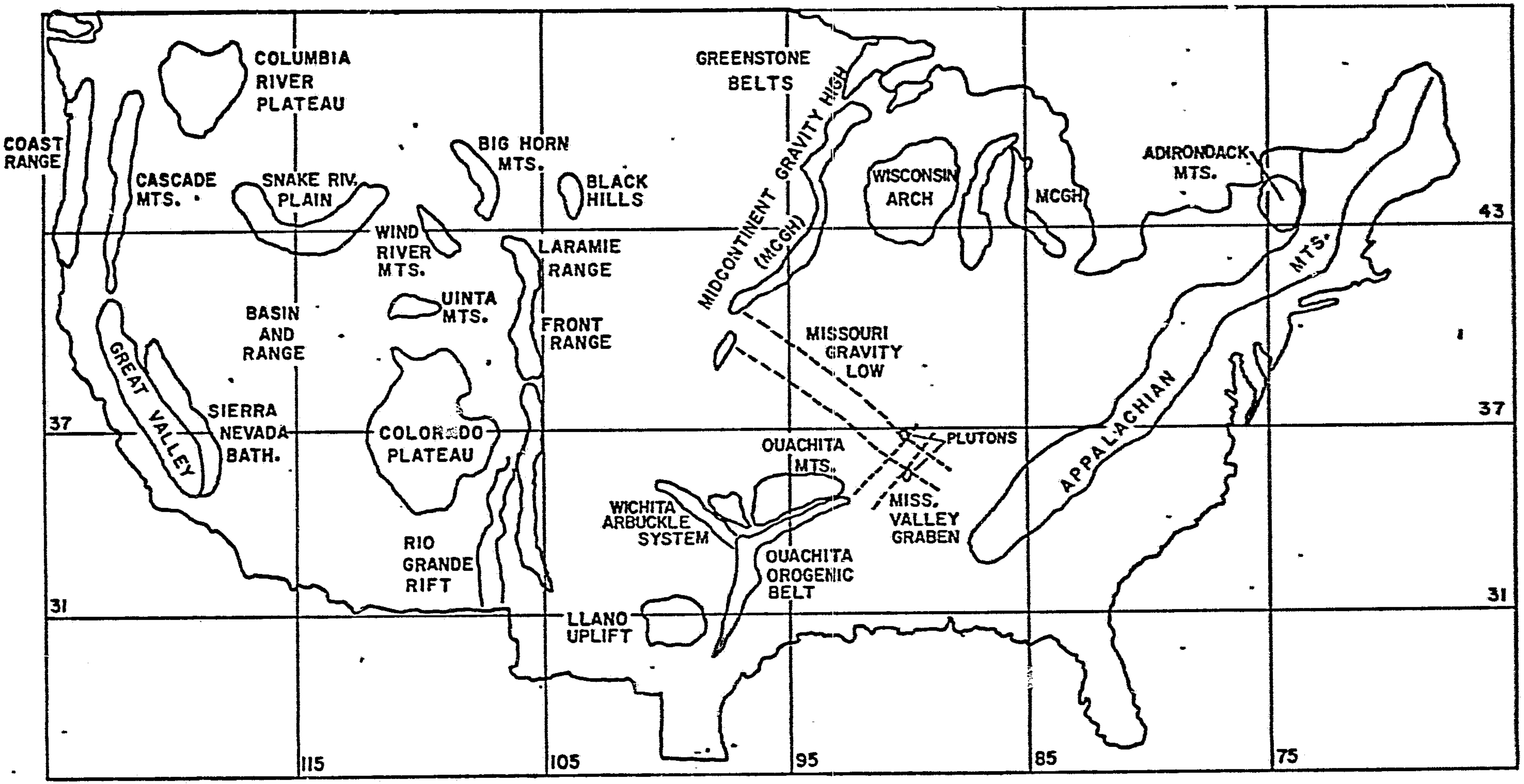

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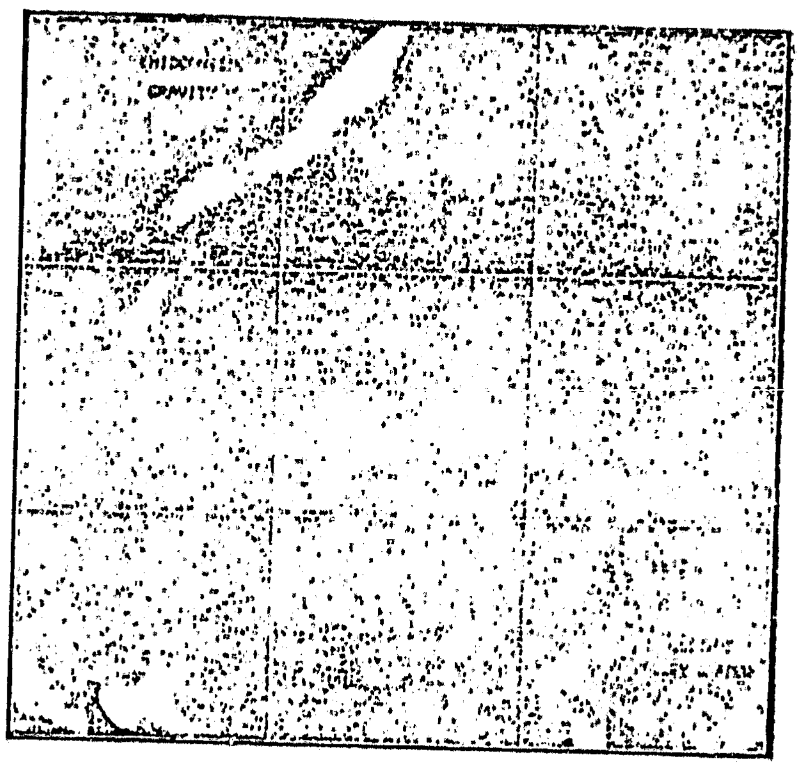
Figure 5



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